Renewable and Sustainable Energy Reviews 37 (2014) 424–434

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

System boundaries of zero carbon buildings

Wei Pan*

Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong, China

ARTICLE INFO

Article history:
Received 20 January 2014
Received in revised form
14 April 2014
Accepted 3 May 2014
Available online 3 June 2014

Keywords:
Zero carbon building
Zero energy
Carbon emission
System boundary

ABSTRACT

Zero carbon building has been regarded as an important approach in reducing the carbon emissions associated with buildings. However, despite significant policy drivers, the uptake of this approach has been low. This paper examines the concepts and develops a theoretical model of the system boundaries of zero carbon buildings. Previous research is largely grounded in the net (nearly) zero carbon/energy parameter and focuses on buildings operations. However, there is increasing awareness of the need for lifecycle approaches to address carbon emissions and for boundaries to be defined to help elaborate the concept and guide research. The developed model covers eight types of boundaries, the policy timeframe, building lifecycle, geographic, climatic, stakeholder, sector, density and institutional boundaries. These boundaries are dynamic and interactive. It is concluded that zero carbon buildings should be regarded as complex socio-technical systems, but should not be exaggerated as surrogates for sustainable buildings. The findings are confirmed with case studies of five pioneering zero carbon buildings worldwide. The case studies demonstrate the great diversity and complexity of zero carbon building boundaries and assert that without the explicit specification of the boundaries, the comparison of cases in different contexts is like "comparing apples to pears."

Contents

* Tel.: +852 2859 2671.
E-mail address: wpan@hku.hk

http://dx.doi.org/10.1016/j.rser.2014.05.015

1. Introduction

Buildings worldwide account for as much as 45% of the total energy consumption and carbon emissions [1], which indicates that buildings are the biggest contributor to anthropogenic climate change. Buildings have therefore been identified as offering the greatest opportunities for reducing carbon emissions [2]. Zero carbon building (ZCB) has been regarded as an important approach for reducing the carbon emissions associated with buildings and has attracted significant policy attention in many countries [3]. For example, the UK government has set ambitious targets to achieve "zero carbon" for new homes from 2016 [4, p. 15] and for non-domestic new buildings from 2019 [5, p. 7]. The recast of the Energy Performance in Buildings Directive (EPBD) of 2010 [6, p. 21] requests that the EU member states ensure that "by December 31, 2020, all new buildings are nearly zero energy buildings (ZEBs) and after December 31, 2018, new buildings occupied and owned by public authorities are nearly ZEBs." Similarly, in the US, the Energy Independence and Security Act of 2007 authorizes the Net-Zero Energy Commercial Building Initiative to support the goal of net zero energy for all new commercial buildings by 2030. It specifies a zero energy target for 50% of US commercial buildings by 2040 and net zero for all US commercial buildings by 2050 [7].

However, despite these significant policy drivers, the up-take of ZCB practices has been low. The total number of ZCBs and similar building schemes worldwide as of June 2013 was less than 300 [8]. Researchers have attempted to determine the contributing factors to the low up-take by examining ZCB and similar approaches (e.g., ZEB) in relation to their definitions (Torcellini et al. [9]; Hernandez and Kenny [10]; Sartori et al. [11]), calculation methodologies (Marszal et al. [12]), policies (McLeod et al. [13] and Kilbert and Fard [14]) and construction activities (Panagiotidou and Fuller [15]). These studies suggested that there are significant challenges preventing the up-take of ZCB. Pan [16] summarized the challenges as a lack of understanding of the ZCB principles, insufficient and inconsistent ZCB practices, unclear and uncertain ZCB policies and conflicting ZCB priorities in management. Underlying all of these challenges is a lack of knowledge of the theoretical grounds and boundaries of ZCB.

In addressing these gaps in knowledge, this paper contributes an innovative theoretical approach. ZCBs are regarded as complex socio-technical systems that cannot be effectively examined without explicitly defining their boundaries. This systems approach is essential, as all carbon reduction strategies involve political, economic, technical, social and behavioral factors [17] that connect multiple stakeholders such as practitioners, occupants and researchers. Although researchers have suggested systematically addressing the issues related to energy supply and demand and connecting the multiple stakeholders [18,19], the systems approach has seldom been made explicit in ZCB research. The aim of this paper is to develop a theoretical model of the system boundaries of ZCBs. Following the introduction, the paper critically reviews ZCB concepts and examines the theoretical grounds. It develops a theoretical model of the ZCB system boundaries and verifies the model using case studies of pioneering ZCBs across the world. The paper then discusses the implications of the developed model on future ZCB research, policy and practices.

2. ZCB concepts

Although the term ZCB is new, the concept builds on research into low carbon/energy buildings that dates back to the 1940s and has been growing in the last two decades [20]. The term ZCB is sometimes used interchangeably with many related but different terms.

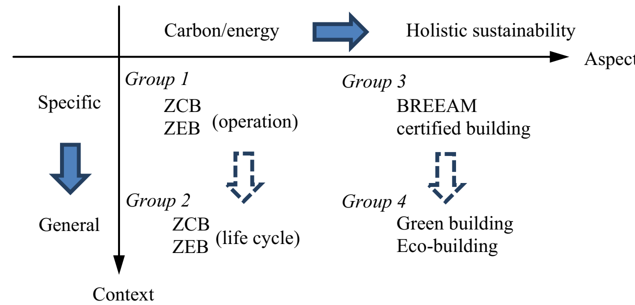

Fig. 1. Model of the categorized ZCB-related terms.

2.1. The terms describing ZCB

A survey carried out by Concerted Action in support of the EPBD in 2008 identified 17 different terms used across Europe to describe low or zero carbon and energy buildings [21]. This was expanded in a follow-up Concerted Action report [22] that presented 23 different terms for "high performance buildings" used in 14 EU member states. Erhorn and Erhorn-Kluttig [22, p. 3] commented that these terms could broadly be categorized as referring to

- "low energy consumption (low energy house, energy saving house, ultra-low energy house, 3-litre-house, zero heating energy house, zero energy house, plus energy house, very low energy house, energy self-sufficient house and energy autarkic house),
- low emissions (zero emission house, zero carbon house, emission-free house and carbon free house) or
- sustainable or green aspects (eco-buildings, green buildings, code for sustainable homes, bioclimatic house and climate: active house)."

Erhorn and Erhorn-Kluttig [22, p. 3] added, "One of the terms refers to a national standard (Lider A used in Spain), whereas two others refer to private organizations (passive houses) or public bodies (Building Research Establishment Environmental Assessment Method (BREEAM) buildings). Some of the terms for high performance buildings try to incorporate more than one of the mentioned issues (triple zero house and total quality planning and rating)."

Riedy et al. [23, p. iv], in their review of the definitions of "zero emission buildings," identified many similar terms in common use, such as "near zero energy; zero energy; zero net energy; passive house; energy plus; fossil fuel free; 100% renewable; zero carbon; net zero carbon; carbon neutral; climate neutral; climate positive and positive development." The Low Carbon Construction Innovation and Growth Team [24, p. 6] criticized that the shifting terminologies and the number of tools and methodologies that sometimes lead to quite different answers to the same questions have contributed a major barrier to the progress of achieving a low carbon future, "Carbon can sometimes mean carbon, sometimes carbon dioxide and sometimes a carbon dioxide equivalent, and the definition of zero carbon is far more complex than that rightly aspirational term might suggest." The ZCB concept is further complicated by concepts that take into account more parameters than carbon/energy and use special terms such as green building or eco-building, such as those listed by Erhorn and Erhorn-Kluttig [22].

The many terms in use depict a complicated profile of the concept of ZCB. This paper argues for a reduction in complexity by using two fundamental dimensions of the terms, the aspect being described and the context under discussion (Fig. 1). The paper categorizes the many ZCB-related terms into four groups:

Group 1	Carbon/energy-based terms within a specific context, divided into carbon emission-based, such

	as ZCB and zero emission building; and energy consumption-based, such as ZEB and nearly ZEB.
Group 2	Carbon/energy-based terms within the general context, e.g. lifecycle ZCB and ZEB.
Group 3	Broad aspect terms with a scope broader than carbon/energy within a specific context, for example, buildings certified to BREEAM originated in the UK but have been widely used elsewhere and buildings certified to BEAM Plus in Hong Kong.
Group 4	Broad aspect terms within the general context, such as green building and eco-building.

In addition to categorizing the terms, a further understanding of the concept of ZCB also requires examining the definitions.

2.2. *The definitions of ZCB*

The many terms describing ZCB differ in terms of their aspects and contexts, which contributes to the complexity of the definitions of and calculation methods for ZCB. ZCB has been included in the building energy policies, codes and/or regulations of many countries, either as ZCB or a related term [3]. This paper examines the definitions of ZCB within the context of the countries that typically lead the policies and practices of delivering ZCBs.

The UK was the first country to set a timetable for delivering ZCBs. The development and evolution of the definitions of ZCB in the UK has contributed significantly to the understanding of ZCB worldwide. The UK definitions of ZCB assume net zero carbon emissions over one year. Crucial debate exists on the scope of the energy with which carbon emissions are associated, ranging from the originally proposed "genuine" or "complete" zero carbon (which includes both regulated energy for space heating, cooling, ventilation, lighting and hot water; and unregulated energy for cooking, washing and electronic entertainment appliances [4, p. 7]) to regulated energy only [25, p. 117]. Also under debate is the three-tier hierarchy of measures for achieving zero carbon, "energy efficiency," "carbon compliance" and "allowable solutions" [26]. These three measures should cover all of the expected regulated and unregulated emissions from the home [26]. However, the allowable solutions measure has been criticized as "it does not directly address the source of the problem and as such is vulnerable to the issues which affect carbon offset mechanisms in general" [13, p. 29]. It is effectively a form of indirect carbon offsetting, which some researchers (e.g., Bullock et al. [27]) have argued it does not lead to emission reductions. ZCB definitions in the UK have focused on dwellings and the government expects to use the same definition for non-domestic buildings.

In ***Australia***, Sustainability Victoria on behalf of the Australian Sustainable Built Environment Council commissioned a study by Riedy et al. [23, p. viii] to develop a definition of ZCB for Australia, which is

"A ZCB is one that has no net annual Scope 1 and 2 emissions from the operation of building-incorporated services.

- Building-incorporated services include all of the energy demands or sources that are part of the building fabric at the time of delivery, such as the thermal envelope (and associated heating and cooling demand), water heater, built-in cooking appliances, fixed lighting, shared infrastructure and installed renewable energy generation.
- ZCBs must meet specified standards for energy efficiency and on-site generation.
- Compliance is based on the modeling or monitoring of greenhouse gas emissions in kg CO_2-e/m^2/yr."

This definition is clearly also based on the net ZCB concept.

In the ***EU***, a "nearly ZEB" is defined by the recast EPBD of 2010 [6, p. 21] as "a building that has a very high energy performance… The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby." This definition addresses energy rather than carbon and is again based on the net concept, but it offers flexibility in achieving the "nearly zero" target.

Within the ***US*** context, Torcellini et al. [9, p. 5] proposed several ZEB definitions depending on the boundary and metric of the ZEB:

- Net Zero Site Energy: a site ZEB that produces at least as much energy as it uses in a year, when accounted for at the site.
- Net Zero Source Energy: a source ZEB that produces at least as much energy as it uses in a year, when accounted for at the source.
- Net Zero Energy Costs: the amount of money that the utility pays the building owner for the energy that the building exports to the grid is at least equal to the amount that the owner pays the utility for the energy services and energy used over the year.
- Net Zero Energy Emissions: a net zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

These definitions refer to ZEBs that use supply-side options available on-site. Torcellini et al. [9, p. 4] used the term "off-site ZEBs" to denote ZEBs that have a portion of their renewable generation supplied by off-site sources. These definitions are based on the net ZEB concept, but introduce boundaries to help elaborate the concept.

3. Previous research and reflections on the definitions of ZCB

There have been research attempts to address the complexity and inconsistency in the definitions of ZCB. An important reflection is on the scope of the net zero carbon/energy target. The terms describing zero energy/emission/carbon buildings can be interpreted in different ways and should be analyzed with care. According to the Concerted Action report [22, p. 4], "buildings [nearly ZEBs] can either be defined as to consume no energy or emit no carbon at all… or they can be defined as yearly balanced buildings. In this case, the buildings still consume energy, but produce in one period of the year at least as much energy as they need during the whole year… Thus, the buildings have the same definitions as energy/emission/carbon neutral buildings." The International Energy Agency's Solar Heating and Cooling Task 40 reviewed a range of ZEB definitions and calculation methods from Austria, Canada, Denmark, Germany, Italy, Norway, Switzerland and the US. This review revealed that the eight countries had a common energy balance approach based on the principle of no energy use beyond the renewable energy generated, but that the elements and boundaries of this energy balance varied [12]. Erhorn and Erhorn-Kluttig [22, p. 4] elaborated that "some of the definitions only cover part of the energy uses that have to be assessed according to the EPBD. For example, not all of them include domestic hot water or cooling energy use." Other researchers (e.g., Hernandez and Kenny [10]) expanded the energy in use and proposed the "life cycle ZEB," a building whose primary energy use in operation plus the energy embedded in its materials and systems over the life of the building is equal or less than the energy produced by renewable energy systems within the building.

Another important reflection is on the parameters that differ between the ZEB definitions. Marszal et al. [12] suggested that the seven most important issues in defining ZEB are the metric of the balance, the balancing period, the type of energy use included in the balance, the type of energy balance, the accepted renewable energy supply options, the connection to the energy infrastructure and the requirements for energy efficiency, the indoor climate and, in the case of grid-connected ZEBs, for the building–grid interaction. The framework proposed by Marszal et al. [12] advances the systems thinking of Torcellini et al. [9] by defining ZEBs depending on their boundaries and metrics. Sartori et al. [11] described the characteristics of net ZEBs using the five criteria and sub-criteria of the building system boundary (the physical boundary, balance boundary and boundary conditions), weighting system (the metrics, symmetry and time dependent accounting), net ZEB balance (the balancing period, type of balance, energy efficiency and energy supply), temporal energy match characteristics (the load matching and grid interaction) and measurement and verification. Their framework explored the boundaries of ZEBs and embedded the systems approach. However, the boundaries considered were still limited, suggesting room for a further systemic analysis of the socio-technical contexts of ZCBs.

Acknowledging that the ZCB terminologies and definitions are potentially confusing and pose problems for communication, Riedy et al. [23] identified a number of key points of difference. These are the life cycle boundary, assessment methods and metrics, timeframe, grid connection, sector differences, building type, spatial boundary, allowable emission reduction options and conditional requirements. This framework for analyzing ZCB-related definitions expanded the components and boundaries of ZCBs that were identified in previous research (e.g., by Torcellini et al. [9] and Marszal et al. [12]) and was useful for shaping a suitable definition. However, the theoretical ground on which the "key points of difference" was identified is unclear, which impairs the quality of comparisons with existing definition frameworks and therefore limits its transferability. Systems thinking is implicitly reflected in this framework as it includes multiple boundaries (by covering time and spatial dimensions, for example) and "conditional requirements" (non-carbon/energy criteria, such as comfort standards and cost limits) that must be met to deliver a ZCB. However, the systems thinking is still fragmented, with little explanation of its supporting theories. The "key points" also mix the boundaries with the assessment methods and requirements of ZCBs, which demands further clarification of the boundaries in the systems approach.

A further important reflection is that the value-based context-specific nature of the ZCB concept appears frequently in the existing literature. Torcellini et al. [9] acknowledged that appropriate definitions of ZEB depended on the project goals and values of the design team and building owner. The recast EPBD of 2010 [6, p. 21] specified that "the [EU] member states must have in their national plans a detailed application in practice of the definition of nearly ZEBs, reflecting their national, regional or local conditions." The Concerted Action report [22] recommended that in future work, "the national applications of the definition of nearly-ZEBs must be made in line with the national assessment methods, including all [of the] boundary conditions" (p. 7) and called for "a common understanding on the use of terminology and the definition of nearly ZEBs" (p. 8). Sartori et al. [11] also argued that different definitions were possible, in accordance with a country's political targets and specific conditions. However, it remains unclear how the concept of nearly ZEB should be interpreted within the specific contexts of the EU member states.

These reflections on ZCB definitions drawing on the examination of previous research call for new knowledge of the ZCB system boundaries. Despite the importance of defining the boundary of a system [28], few previous studies have explicitly examined the boundaries of ZCBs. The limited analysis and discussion of the boundaries fragment our understanding of ZCBs. Thus, new knowledge of ZCB system boundaries is needed. This paper proposes that an understanding of the system boundaries of ZCBs will facilitate a better grasp of the principles of ZCB and consequently inform ZCB practices, policy formulation, reviews and priorities management.

4. Model of the ZCB system boundaries

The system boundaries of ZCBs are defined in this paper as the set of limits that control the way in which ZCBs are examined in a systemic manner. The identification of the boundaries of ZCBs draws on the theoretical examination and resulting reflections on the concept and definitions of ZCBs and is based on the scope, parameters and contexts of ZCB. Eight types of ZCB boundaries are developed, the policy timeframe, building lifecycle, geographical, climatic, stakeholder, sector, density and institutional boundaries. These boundaries together address the key questions of where, when, who and how, in relation to ZCBs (Fig. 2).

4.1. Policy timeframe boundary

The policy timeframe boundary aligns with the climate change, energy and building energy policies and regulations of a country or region, which together shape the future of ZCBs. The typical future milestones of the policy timeframe dimension are grouped as in Fig. 2, into the near future, e.g., 2020, as proposed by the EU's [29] "2020" strategy; the medium-term, e.g., 2030 is the target for achieving nearly ZEBs in the EU [6] and "HK3030" in Hong Kong denotes the proposed reduction by 30% of the absolute electricity consumption in buildings by 2030 from 2005 levels [30]; and the long-term, e.g., 2050, as proposed in the UK for achieving 80% carbon emissions in the UK from the 1990 level [31].

4.2. Building lifecycle boundary

The building lifecycle boundary contextualizes the time dimension at the building project level. Drawing on the literature of life cycle assessment [32], this paper considers the full building lifecycle to cover before-use, use and after-use. These three phases cover the nine key stages of raw materials extraction, transportation to factory, manufacturing, transportation to site, construction and installation, operation, maintenance and refurbishment, deconstruction and recycling or landfill (Fig. 3). Depending on how it covers these stages, a lifecycle may be in the form of cradle to gate, to site, to operation, to grave or to cradle (Fig. 3).

The building lifecycle boundary is directly related to the type of carbon or energy and the metric of the balance of the ZCB.

4.2.1. Type of carbon or energy

The types of carbon or energy generally include building-related regulated carbon/energy (e.g., space heating, hot water, ventilation and internal lighting for domestic buildings in the UK), user-related unregulated carbon/energy (e.g., appliances) in the operation stage of the building lifecycle and embodied carbon/energy in the other stages of the building lifecycle.

In theory, all the three types of carbon or energy should be considered in ZCB as they all make a significant contribution to carbon emissions. For examples, appliances contribute up to 50% of the energy use in new homes in the UK [33, p. 15]. Carbon emissions released during the manufacture and construction of an ultra-low energy dwelling may account for up to 50% of its net 80 year emissions [13]. Energy consumption in buildings as direct

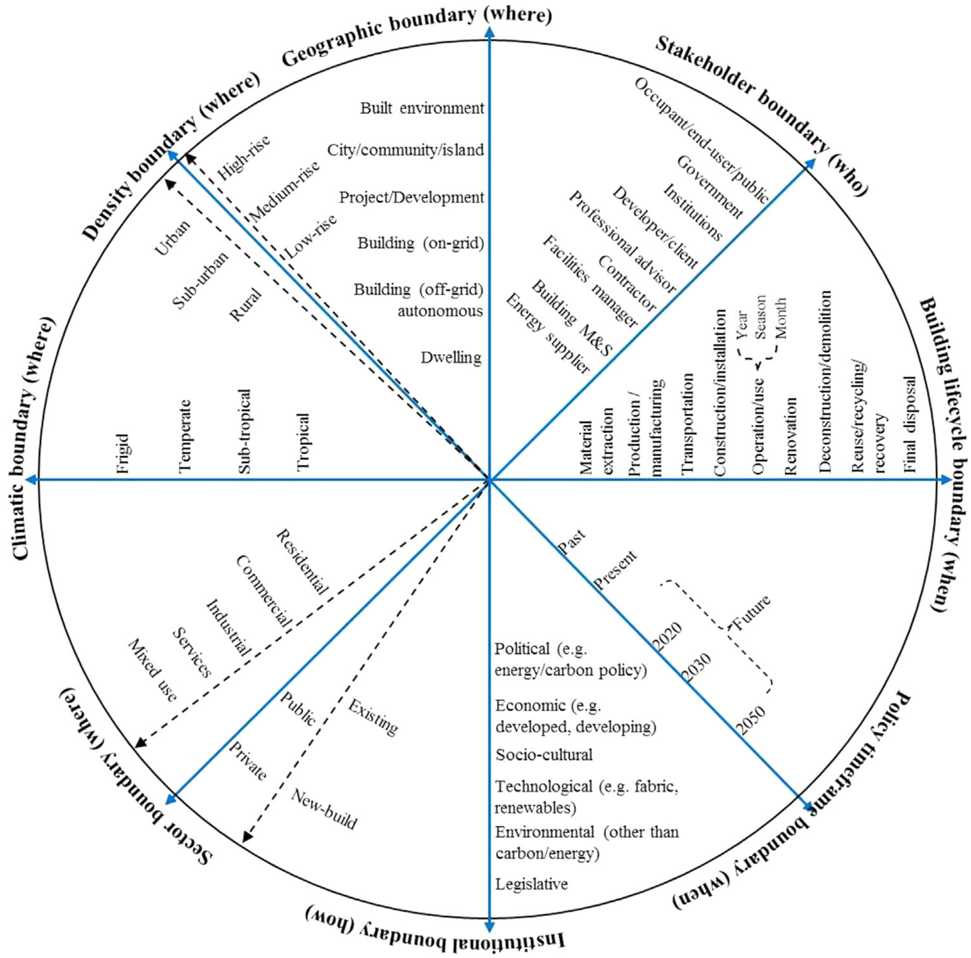

Fig. 2. Model of the ZCB system boundaries.

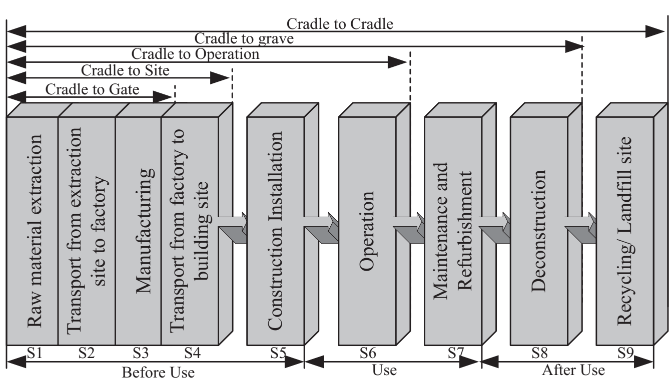

Fig. 3. Conceptual framework of the building lifecycle.

energy services (i.e., regulated and unregulated user-related energy) accounts for about 30% of the total energy consumption in China. The aggregated embodied carbon emissions from the production and transportation of construction materials and components accounts for 19–21% of China's total carbon emissions [34].

In reality, the types of carbon and energy in relation to the building lifecycle stages are interpreted and used in different ways. For example, the United Nations Environment Program's Common Carbon Metric [35, p. 24] only includes the "use" stage "because over 80% of greenhouse gas emissions are emitted during [this] stage" and "these emissions are measurable, reportable and verifiable." Building on the three-phase lifecycle framework, Riedy et al. [23] recommended a hierarchy of ZCB definitions to represent the parts of the building lifecycle that result in emissions associated with the building, occupant, embodied and full lifecycle. The emerging body of knowledge of integrating embodied energy with energy use analysis [10] will inform our interpretation of the building lifecycle boundary.

The carbon or energy balance is usually calculated on an annual basis when the operation stage is the main focus, which enables the full operational influence of the building to be accounted for. The calculations are performed monthly or seasonally in some cases (e.g., the International Energy Agency's solar heating and cooling program in Germany, studied by Marszal et al. [12]) to reduce the demand on the electricity infrastructure, but this is rare. Riedy et al. [23] explained that it was difficult to achieve a zero emissions balance on a shorter timeframe due to seasonal and monthly fluctuations in the availability of on-site renewable energy.

Studies of occupant behavior indicate a large potential for reducing the overall energy use and improving the building economy by motivating energy efficient behavior [36], although this potential may not be easily accessed due to the "rebound effect" [37]. Researchers have argued that the use of user-related energy use in calculations is associated with "high uncertainty and [a] lack of sufficient data/input" [12, p. 977]. In building energy research, "the current use of normative models and the assumption of singular values for key parameters have already been discussed as fundamentally flawed due to issues with their distribution and uncertainty" [18]. There is a lack of accurate,

reliable values/inputs and therefore a lack of interest in the calculation and analysis of the embodied energy [38].

4.2.2. Metric of the balance

The metric of the balance has been debated in the ZCB literature. Torcellini et al. [9] considered the site energy, source energy, energy cost and carbon emissions related to energy use as potential metrics. Kilkis [39] developed a carbon equivalency metric to quantify the compound carbon emissions of net ZCBs. The primary energy is the most favored metric of the net ZEB balance, used for example in the EPBD recast [6], mainly due to the regulatory focus in building energy use. Sartori et al. [11, p. 224] discussed other metrics, such as environmental credits and politically/strategically decided factors, and argued that "the choice of the metrics, especially political factors, will affect the relative value of energy carriers, hence favoring the choice of certain carriers over others and influencing the required (electricity) generation capacity … Political factors can be used to promote or discourage the adoption of certain technologies and energy carriers." This helps to explain the proposed use of the greenhouse gas emissions metric in Australia for ZCBs [23, p. vi]: it reflects "a higher priority on climate change response than energy security" and is consistent with the existing Australian building rating tools and the national greenhouse and energy reporting system.

4.3. Stakeholder boundary

The stakeholder boundary defines the people and organizations that affect and/or are affected by ZCBs and/or the process of achieving ZCBs. A stakeholder analysis helps to prioritize different stakeholders' short-term and long-term interests and to make decisions [40]. Its importance has been increasingly realized in the construction industry [41]. Despite its origin in organizational management [42], the concept of the stakeholder has been broadened in the literature and many studies classifying or grouping stakeholders exist. For example, Winch [43] classified stakeholders in construction projects as internal stakeholders around the client on both the demand and supply sides and external stakeholder, comprising private and public actors. Drawing on systems thinking, this paper identifies four key groups of ZCB stakeholders that affect and/or are affected by ZCBs (Fig. 4):

- The demand group, such as the general public, building occupants and end-users, clients, investors, buyers and the government;
- the supply group, such as developers, professional advisors (e.g., architects, designers, engineers, planners and surveyors), contractors, facilities managers, building manufacturers/suppliers and energy producers and suppliers;
- the regulation group, such as the government and its departments and agencies; and
- the institution group, e.g., financers, bankers, mortgage lenders, universities and professional bodies.

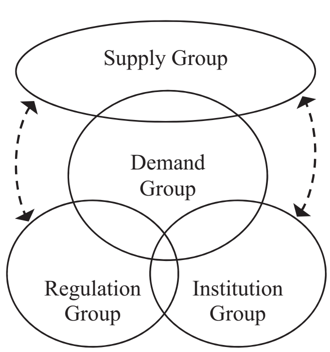

Fig. 4. Conceptual model of the ZCB stakeholders.

Some stakeholders may fall into two groups. For example, government and institutions both demand and regulate ZCBs and those in the supply group also have a demand for buildings.

4.4. Geographic boundary

The geographic boundary denotes the physical location and focus of a ZCB. This boundary has been mentioned in previous ZCB research. For example, Sartori et al. [11, p. 221] proposed that the "physical boundary" can "encompass a single or a group of buildings; determines whether renewable resources are "on-site" or "off-site". However, most studies implicitly referred to the boundary of concern without providing a specific definition or elaborating. Nevertheless, these studies indicated a range of geographic boundary options, such as the "zero energy island" [44], "net zero energy island" [45], "zero carbon eco-cities" [46], and typical ZCBs/ZEBs.

The option of zero carbon/energy at the building level dominates the body of knowledge on ZCBs. The options with a larger boundary than that of a building or a development project, e.g., the zero energy island [44], are rare. Similarly, the autonomous (off-grid) option has also not gained much international attention, but has rather been perceived as an intermediate step towards grid-connected net ZEBs/ZCBs [9]. Sartori et al. [11] argued that the (two-way) grid option was indispensable in defining a net ZEB in the EU member states. However, in the UK, drawing a line between on- and off-site systems is much more complicated, due to the three-tier ZCB policy of energy efficiency, carbon compliance (on-site and connected renewables) and allowable solutions [25].

This paper draws on the previous research to summarize the geographic boundary options of a ZCB (Fig. 5). The boundary options range from a unit of dwelling (e.g., a house or an apartment unit that is part of a building), an autonomous building (multi-occupancy), a grid-connected building, a project or development (such as a cluster of buildings with auxiliary facilities and on-site (and optional off-site) carbon reduction systems), a community or city (of which an island is a sub-option), to the built environment. These boundary options are illustrated with the

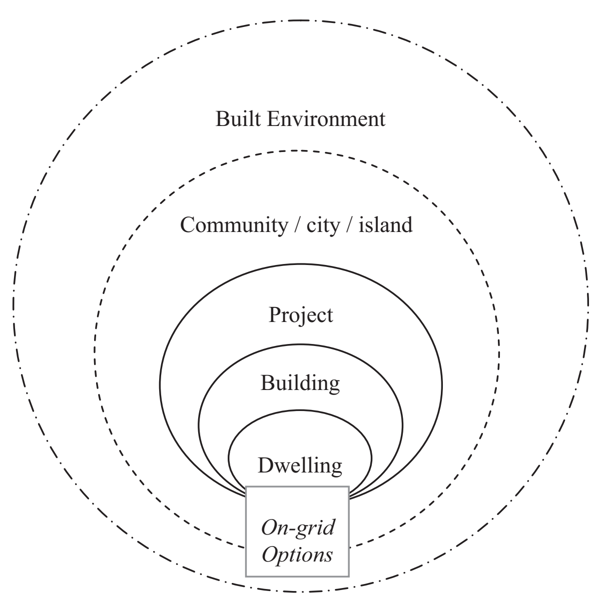

Fig. 5. Conceptual model of the ZCB geographical boundaries.

expanding physical locations and focuses of ZCBs in Fig. 5, the understanding of which will allow geographic interactions by political considerations when defining ZCBs.

4.5. Density boundary

The density boundary of a ZCB denotes the level of density of the building. It can be both technically challenging and expensive to achieve ZCBs in dense urban sites [26]. If the definition of ZCB is too rigid (such as requiring all of the renewable energy to be on-site) or too costly, smaller urban brownfield developments may be prejudiced in favor of larger greenfield sites that offer greater economies of scale in energy supply technologies [26]. Government policies may promote relatively dense forms of urban development to minimize the amount of development that is needed on extra-urban greenfield sites to address a broad range of environmental and social concerns, such as the preservation of biodiversity and green space, minimizing urban sprawl, minimizing carbon emissions from transport and providing good access to the social and community infrastructure.

Another important aspect of the density boundary is the height of ZCBs. Pan and Ning [47] revealed that the vast majority of current ZCBs was low-rise and that high-rise options had been seriously underexplored in both research and practice. This paper therefore splits the ZCB density boundary to address both the height (high-rise, medium-rise or low-rise) and the urban density (urban, sub-urban or rural) of a building (Fig. 2).

4.6. Climatic boundary

The climatic boundary denotes the climatic zones in which a ZCB is located, such as tropical, sub-tropical, temperate and frigid zones. Wilford and Ramos [3], p. 7 stated that “a country often experiencing $-10\ ^{\circ}C$ in winter, such as Austria or Canada, requires more heating energy overall [than] temperate countries like France or the UK.” However, countries in tropical or sub-tropical zones, such as Singapore, may focus much more on cooling energy when delivering ZCBs. Pan and Ning [47] found that the vast majority of ZCBs to date [8] were found in mild or cold climatic regions, whereas few existed in (sub-)tropical regions. The asymmetrical distribution of current ZCBs reflects an imbalanced knowledge of and experience with delivering ZCBs across the world, which hampers effective learning and benchmarking of good practices.

4.7. Sector boundary

The sector boundary denotes the business sectors and types of buildings. The existing global ZCB policies prioritize zero carbon targets for different business sectors. For instance, in the UK, new-build homes built with public funding must be zero carbon by 2015, but other new-build homes must be zero carbon by 2006 [4, p. 15], provided that the technology needed to achieve this cost effectively is available. New non-domestic buildings must be zero carbon from 2019 [5, p. 7], but schools must be zero carbon from 2016 and other public sector buildings from 2018 [31]. In the US, the Department of Energy [48] in the Building Technologies Program aims to achieve marketable zero energy homes in 2020 and commercial ZEBs in 2025.

Different sectors may be associated with different building assessment methods and the feasibility of particular emission reduction options [23]. The sector boundary is therefore important for achieving meaningful comparisons between buildings. This paper therefore proposes using the sector boundary to denote the business sector (whether a building is public or private), type of building (for example, commercial, residential, industrial, services and mixed use by function) and status (for example, new-build or existing) of a building (Fig. 2).

4.8. Institutional boundary

The institutional boundary denotes the institutional context within which ZCB practices are shaped. An established approach for analyzing institutional contexts is the political, economic, socio-cultural, technological, environmental and legislative analysis framework (PESTEL). The aspects covered in the PESTEL framework have been somewhat reflected in previous ZCB research, but often only implicitly. For example, Marszal et al. [12] suggested that indoor climate requirements should be included in the ZEB definition and that the economy was very important in practice and for the future wider implementation of the concept, although it has been ignored in the ZEB definition literature. Wilford and Ramos [3] commented that countries running mainly on nuclear power would have lower carbon emissions overall compared to those running mainly on coal, implying that the ZCB policy of countries was largely subject to their energy fuel mix and energy policies. McLeod et al. [13] investigated the definitions of zero carbon homes in the UK and contended that the economic downturn was undoubtedly a factor influencing UK ZCB practice and policy.

This paper therefore explicitly groups the ZCB institutional boundaries into the PESTEL aspects. Although the PESTEL aspects may be too wide-ranging to be addressed practically, they should help to understand the institutional boundaries of ZCBs in a structured manner. The PESTEL aspects may help to explicitly identify the socio-technical aspects of ZCBs other than the carbon/energy parameter and therefore to link ZCBs and concepts that possess a broader scope, such as green buildings and eco-buildings. It is worth noting that building energy research has started to use holistic research approaches that address buildings as complex systems [18,34]. Nevertheless, this paper cautions that attempts to exaggerate ZCBs as a surrogate for the entirety of environmental, social and economic sustainability will be vague and unrealistic, as ZCBs are complex systems that are influenced by their contexts, as elaborated in the eight system boundaries examined here.

4.9. Dynamic and interactive nature of the system boundaries

Although the boundaries are described separately, they are dynamic and interact with each other. For example, the institutional boundary changes with the policy timeframe, as the PESTEL contexts evolve. The building lifecycle and stakeholder boundaries interact with each other to determine the type of carbon or energy for the ZCB calculations. Contractors may be more interested in the construction/installation stage of the building lifecycle, whereas facilities managers may be more concerned with the operation stage. Associated with these stages are different carbon/energy calculation methods and ZCB definitions.

The geographic and stakeholder boundaries also interact. ZCBs can be achieved with a grid connection, relying on energy efficiency and usually on-site renewable energy, or without a grid connection, using the grid to help achieve the net zero carbon. Sartori et al. [11] suggested reducing the energy demand using energy efficiency measures and generating electricity and thermal energy carriers using energy supply options to achieve a net ZEB balance.

The sub-options within a boundary may also interact. For example, public and private residential and commercial buildings often have differently prioritized zero carbon targets. Therefore, the identification and defining of the ZCB boundaries should not

be a solely scientific or engineering process, but should be dynamic and reflect socio-political preferences.

5. Case studies of pioneering ZCBs

The developed model of ZCB system boundaries is verified using five pioneering ZCB cases from around the world, the Construction Industry Council ZCB [49] in Hong Kong (Fig. 6), the Building and Construction Authority Academy ZEB [50] in Singapore (Fig. 7), the Melink net ZEB [51] in Cincinnati, Ohio, US. (Fig. 8), the Pixel carbon neutral building [52] in Melbourne, Australia (Fig. 9) and the BOLIG+ZEB [53] in Aalborg, Denmark.

The cases were selected using the purposive sampling principle [54] to cover as many boundary dimensions as possible for comparison and to increase information accessibility (Table 1).

The selected ZCBs have a great diversity of boundary dimensions, which are illustrated in a set of five radar maps (Fig. 10). Several key observations emerge from the comparative analysis:

- On the "when" related boundaries, the Pixel carbon neutral building claims net savings in its annual operational emissions that counterbalance its annual embodied emissions over 50 years. The other cases focus on the operation of the building only, which clearly indicates the principle of net ZCB over a period of one year.
- On the "who" related boundaries, the cases indicate varied driving forces, such as the government, developers and institutions. Despite the specific driving forces, multiple stakeholders are clearly engaged in the development of the ZCBs.
- On the "where" related boundaries, the ZCB cases are largely three story buildings, with a maximum height of 10 stories, suggesting a serious paucity of knowledge and practices for achieving zero carbon in high-rise buildings. The dimensions of the ZCB cases against the geographic, density, climatic and sector boundaries show great diversity. This diversity is partly attributable to how the cases were selected for the study, but also illustrates the increasing awareness and practice of ZCB globally.
- On the "how" related boundaries, despite the complexity of the institutional (PESTEL) ZCB contexts, all of the cases of ZCBs are politically supported and promoted with public and social engagement and use on-site renewable energy systems, typically photovoltaic panels, and energy efficiency measures.

Fig. 6. The first ZCB in Hong Kong (*Courtesy of Construction Industry Council*).

Fig. 7. The first ZEB in Singapore (*Courtesy of Building and Construction Authority*).

Fig. 8. Melink ZEB, Cincinnati, Ohio (*Courtesy of Melink Corporation*).

Fig. 9. Pixel Carbon Neutral Building, Melbourne (*Courtesy of CBRE*).

The case studies suggest that the use of the boundary framework gives insights into, and an effective comparison of the principles, policies and practices associated with ZCBs.

6. Implications of the system boundaries

The developed ZCB system boundaries contribute an innovative approach for examining ZCBs in a systems-integrated manner. The system boundaries have significant implications for future ZCB research, practices, policy formulation and reviews and priorities management.

The system boundaries provide a structured framework for an effective cross-comparison of the principles, policies, practices and priorities of ZCB in different contexts in future research. Cross-comparison is important as it will develop advanced ZCB knowledge in a global context. The use of the boundaries will help to expand the current, largely descriptive, ZCB research in more explorative directions, which will enable an in-depth understanding.

The system boundaries will support both wide and deep learning, which will lead to an accelerated up-take of ZCB

Table 1
Selected ZCBs for system boundary verification.

Boundary	CIC ZCB [49]	BCA ZEB [50]	Melink [51]	Pixel Building (Zuo et al. [52])	BOLIG+(Marszal & Heiselberg [53])
Policy timeframe	Completed in 2012; BEAM Plus Platinum; the first ZCB in HK	ZEB officially opened in 2009; the first ZEB in Singapore	LEED Gold New Construction 2006; LEED Platinum Existing Building 2010; achieved net-zero energy 2011	Highest Green Star score (105 points); The first carbon-neutral office building in Australia by GBCA	Concept in 2005, winning project in 2009; the first demonstration of multi-storey residential net ZEB in Denmark
Building lifecycle	Operation/use stage; Net ZCB over a year; considered embodied carbon	Net ZEB over a year	Operation/use stage; net ZEB over a year	Carbon neutral; net savings in annual operational emissions offset annual embodied carbon over 50 yrs	Net ZEB over a year
Stakeholder	Government; client; user; CIC	Government; client; user; BCA	Developer; user; Melink Corp.	Developer	Institutions: BOLIG+organisation
Geographical	Building with on-site energy supply, not grid connected at the time	Building (on-grid)	Building (on-grid) with on-site energy supply	Building (on-grid) with on-site energy supply	Building (on-grid)
Density (height, size)	3 storeys including basement; a footprint of approximately 1400 m^2	3 storeys; 4500 m^2	Low-rise (2 storeys); 2902 m^2;	Medium-rise; small scale; 4 floors with GFA 1000 m^2, with roof garden	Medium-rise; part 6-stories & 10 stories; 7000 m^2; 114 modules averaged 61.4 m^2
Density (area)	Urban	Urban	Suburban	Suburban	Urban
Climatic	Hong Kong; humid subtropical	Singapore; tropical	Cincinnati, Ohio, US: climatic transition zone, humid subtropical to humid continental	Carlton, Melbourne, Australia; Moderate oceanic climate; changeable conditions	Aalborg, Denmark; humid continental climate with warm summers and no dry season
Sector (building type)	Office and public use	Government office and academic facilities	Both manufacturing and office functions	Commercial office with retail	Residential
Sector (public/ private)	Public; invested by Development Bureau	Public; investment of S$11 m by BCA	Private	Private; investment of A$6 m	Private
Sector (new-build/ existing)	New-build on a brownfield site	Renovation of an existing school building	Initially new-build in 2006 and then renovated in 2011	New-build	New-build
Institutional (PESTEL aspects)	The first ZCB in HK for demonstration and education; passive design, green active systems, bio-fuel tri-generation system, PV panels, low embodied carbon materials	Government R&D project; passive design & active solutions: energy efficient building systems and equipment; 1540 m^2 PV panels on roof; active control: management and optimization and user discipline	Energy efficient building design; on-site PV and wind turbine; geothermal, solar thermal and biomass systems to offset building energy use; and optimized building control	Material selection is critical, like using pixelcrete, second hand access flooring, second hand carpet tiles, recycled timber, low-VOC paints, second hand photovoltaic cells, and doubled glazing	The first net ZEB in Denmark; reduce energy use to minimum, apply renewables to offset remaining energy use; 1782 m^2 PV with 203 m^2 PV thermal and a solar heat pump

practices in future projects. Defining the boundaries of ZCBs at the project or organizational level will help the project team or organization to achieve a systems-integrated understanding of the ZCB of interest and thus a more informed management strategy. Global ZCB practices can be examined in future research to reveal any patterns of good practice.

The boundaries will help to enhance the practicality and achievability of ZCB policies through policy formulation and review, as they provide a framework for explicitly identifying the contexts and engaging multiple stakeholders. The model should be transferrable, but the specific boundary options may need to be adapted to the specific political, social and geographic contexts. This argument echoes the suggestion by Sartori et al. [11, p. 221] that “every country has the need to adapt the net ZEB definition to its own specific conditions, e.g., defining the primary energy or carbon emission conversion factors for the various energy carriers, establishing requirements on energy efficiency or prioritizing certain supply technologies.”

The developed system boundaries provide a foundation on which to compare and contrast ZCBs and sustainable buildings for the management of priorities. Although carbon/energy is an important and often compulsory category in environmental assessment methods and tools, there is no explicit link between achieving zero carbon and improving environmental sustainability. A highly scored “sustainable” building may therefore not achieve zero carbon and a ZCB may not score highly in its overall environmental sustainability. A ZCB or an environmentally sustainable building may not prove to be economically or socially sustainable, as suggested by the ZCB and sustainable buildings literature [24,55] and as perceived by stakeholders in general [56]. Therefore, it is imperative to use the systems boundaries to elicit transferrable lessons and develop meaningful management strategies.

7. Conclusions

This paper examined the concepts of ZCB and developed a theoretical model of the ZCB system boundaries. There are many terms describing ZCB, which all align with two dimensions: the aspect being described, ranging from carbon/energy to holistic sustainability, and the context being covered, ranging from specific to general. Previous ZCB research has largely focused on the net (nearly) zero carbon/energy parameter and buildings operations. However, there is rising awareness of the lifecycle approach for addressing carbon emissions and energy consumption, and the introduction of various boundaries to help elaborate the concept and shape future research. A systems understanding of ZCB must consider the scope of the (net) zero carbon/energy target, the parameters covered and the value-based context-specific nature of

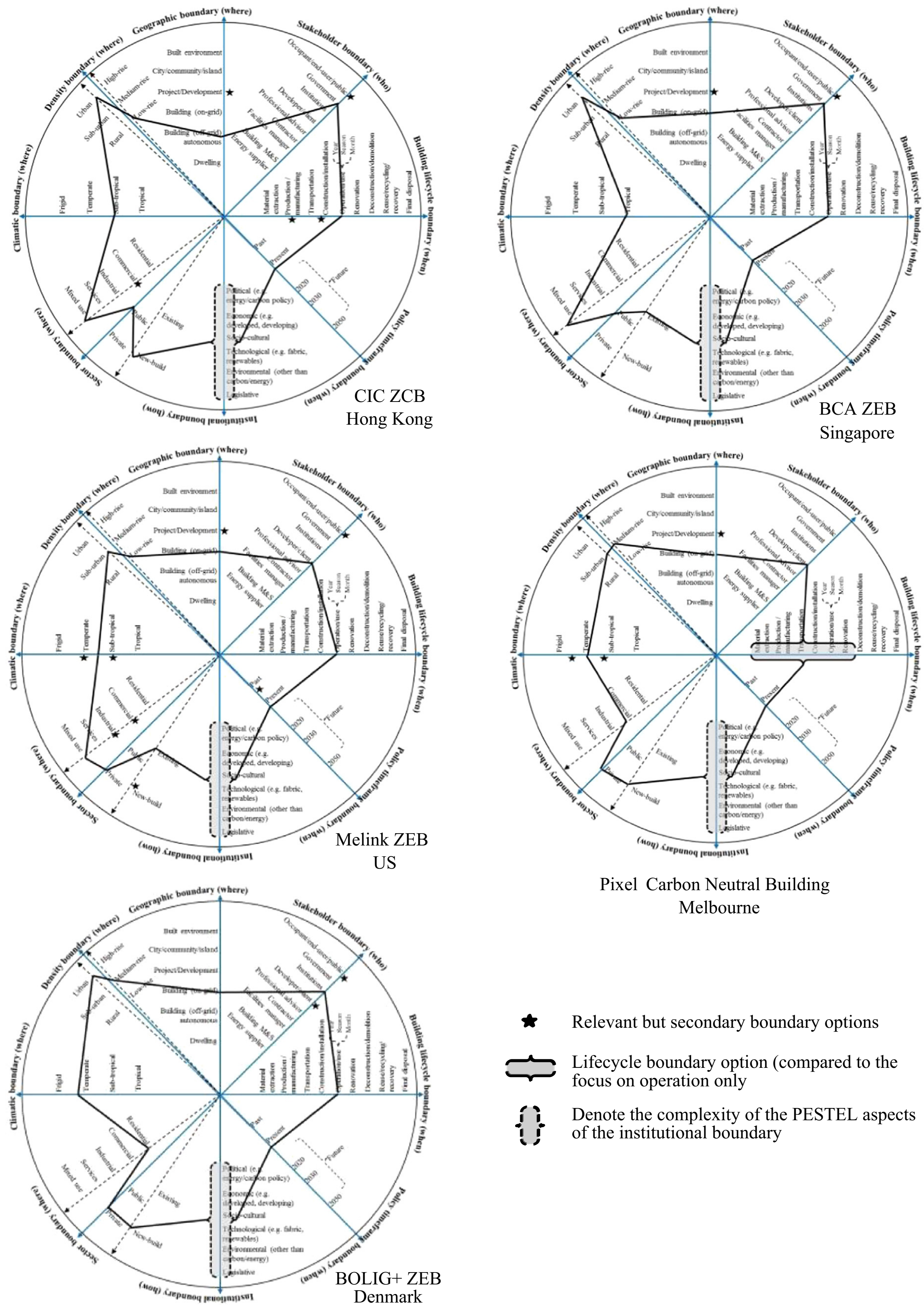

Fig. 10. Comparative boundary profiles of the selected ZCBs. *Note*: See Fig. 2 for a clearer version of the boundary options.

ZCB. ZCBs should be regarded as complex socio-technical systems, but should not be exaggerated as surrogates for sustainable buildings, which have a broader scope than simply achieving zero carbon/energy.

The developed model of ZCB system boundaries covers eight types of boundaries, the policy timeframe, building lifecycle, geographical, climatic, stakeholder, sector, density and institutional boundaries. The boundaries are dynamic, and some interact with each other. The boundaries must be explicitly specified to achieve an effective understanding of ZCBs in a systems-integrated manner.

The model was examined using case studies of five pioneering ZCBs across the world. The use of the model demonstrated the great diversity and complexity of the boundary dimensions of the ZCBs and gave insights into their comparative profiles. The findings asserted that without explicit definition and specification of the boundaries, comparing ZCBs in different contexts would be like "comparing apples with pears."

The developed model has useful implications for future ZCB research, practices, priorities management and policy formulation and reviews. Future research can cross-compare the principles, policies, practices and priorities of ZCBs against the examined boundaries, which should elicit useful information for further debate.

Acknowledgement

I would like to acknowledge the assistance of Yan Ning for identifying the cases of zero carbon buildings.

References

[1] Butler D. Architects of a low-energy future. Nature 2008;452(3):520–3.
[2] IPCC. Climate Change 2007, Fourth IPCC Assessment Report, Intergovernmental Panel on Climate Change; 2007.
[3] Wilford C, Ramos M. Zero carbon compendium: who's doing what in housing worldwide. Amersham: NHBC Foundation; 2009.
[4] DCLG. Building a greener future: towards zero carbon development: consultation. London: Department for Communities and Local Government (DCLG); 2006.
[5] Treasury HM. Budget 2008 stability and opportunity: building a strong, sustainable future. London: The Stationery Office; 2008.
[6] EU. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union; 2010. ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:EN:PDF⟩.
[7] Crawley D, Pless S, Torcellini P. Getting to net zero. ASHRAE J 2009;51(9):18–25.
[8] Musall E Net zero energy buildings – worldwide. ⟨http://batchgeo.com/map/net-zero-energy-buildings⟩; 2013 [accessed 27.09.13].
[9] Torcellini P, Pless S, Deru M, Crawley D. Zero energy buildings: a critical look at the definition. In: Proceedings of the ACEEE summer study. California, USA; Aug 14–18, 2006.
[10] Hernandez P, Kenny P. From net energy to zero energy buildings: defining life cycle zero energy buildings (LC-ZEB). Energy Build 2010;42:815–21.
[11] Sartori I, Napolitano A, Voss K. Net zero energy buildings: a consistent definition framework. Energy Build 2012;48:220–32.
[12] Marszal AJ, Heiselberg P, Bourrelle JS, Musall E, Voss K, Sartori I, et al. Zero energy building – a review of definitions and calculation methodologies. Energy Build 2011;43(4):971–9.
[13] McLeod RS, Hopfe CJ, Rezgui Y. An investigation into recent proposals for a revised definition of zero carbon homes in the UK. Energy Policy 2012;46:25–35.
[14] Kibert CJ, Fard MM. Differentiating among low-energy, low-carbon and net-zero-energy building strategies for policy formulation. Build Res Inf 2012;40(5):625–37.
[15] Panagiotidou M, Fuller RJ. Progress in ZEBs—a review of definitions, policies and construction activity. Energy Policy 2013;62:196–206.
[16] Pan W. Zero carbon buildings: contexts, challenges and strategies. Build J 2013;January:71–3.
[17] Lomas KJ. Carbon reduction in existing buildings: a transdisciplinary approach. Build Res Inf 2010;38(1):1–11.
[18] Summerfield AJ, Lowe R. Challenges and future directions for energy and buildings research. Build Res Inf 2012;40(4):391–400.
[19] Pan W, Garmston H. Building regulations in energy efficiency: compliance in England and Wales. Energy Policy 2012;45(6):594–605.
[20] Carrilho da Graca G, Augusto A, Lerer MM. Solar powered net zero energy houses for southern Europe: feasibility study. Sol Energy 2012;86:634–46.
[21] European Commission. Low energy buildings in Europe: current state of play, definitions and best practice. Brussels: European Commission; 2009.
[22] Erhorn H, Erhorn-Kluttig H. Terms and definitions for high performance buildings, concerted action report, European Union; 2011.
[23] Riedy C, Lederwasch A, Ison N. Defining zero emission buildings – review and recommendations: final report. Prepared for sustainability victoria by the Institute for Sustainable Futures. Sydney: University of Technology; 2011.
[24] HM Government. Low carbon construction innovation & growth team final report. London: Department for Business, Innovation and Skills; 2010.
[25] HM Treasury. The Plan for Growth. London: HM Treasury; 2011.
[26] DCLG. Definition of zero carbon homes and non-domestic buildings: consultation. London: Department for Communities and Local Government (DCLG); 2008.
[27] Bullock S, Childs M, Picken TA. Dangerous Distraction. Why offsetting is failing the climate and the people: the evidence. London: Friends of the Earth (England, Wales and Northern Ireland); 2009.
[28] Skyttner L. General systems theory: problems, perspective, practice. 2nd edition. Singapore: World Scientific Publishing; 2005.
[29] European Union. Directive 2009/28/EC of the European parliament and of the council of 23 April 2009. Official Journal of the European Union, 5.6.2009. ⟨http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:en:PDFS⟩ [accessed 18.01.12].
[30] HKGBC. HK3030: a vision for a low carbon sustainable built environment in Hong Kong by 2030. Hong Kong: Hong Kong Green Building Council; 2012.
[31] HM Government. Climate change act 2008. London: Her Majesty's (HM) Government; 2008.
[32] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of buildings: an overview. Energy Build 2010;42(10):1592–600.
[33] DCLG. Building a greener future: policy statement. London: Department for Communities and Local Government (DCLG); 2007.
[34] Li B, Yao R. Building energy efficiency or sustainable development in China: challenges and opportunities. Build Res Inf 2012;40(4):417–31.
[35] UNEP SBCI. Common carbon metric: protocol for measuring energy use and reporting greenhouse gas emissions from building operations, United Nations Environment Programme Sustainable Buildings & Climate Initiative; 2010.
[36] Masoso OT, Grobler LJ. The dark side of occupants' behaviour on building energy use. Energy Build 2010;42(2):173–7.
[37] Druckman A, Chitnis M, Sorrell S, Jackson T. Missing carbon reductions? Exploring rebound and backfire effects in UK households Energy Policy 2011;39(6):3572–81.
[38] Dixit MK, Fernandez-Solis JL, Lavy S, Culp CH. Identification of parameters for embodied energy measurement: a literature review. Energy Build 2010;42(8):1238–47.
[39] Kilkis S. A new metric for net-zero carbon buildings. In: Proceedings of the energy sustainability conference. Long Beach, California; 2007.
[40] Carroll AB. The pyramid of corporate social responsibility: toward the moral management of organizational stakeholders. Bus Horiz 1991;34(4):39–48.
[41] Newcombe R. From client to project stakeholders: a stakeholder mapping approach. Constr Manag Econ 2003;21(8):841–8.
[42] Freeman RE. Strategic management: a stakeholder approach. Boston: Pitman; 1984.
[43] Winch GM. Managing construction projects: an information processing approach. Oxford: Blackwell; 2002.
[44] Bagci B. Towards a Zero Energy Island. Renew Energy 2009;34(3):784–9.
[45] Praene JP, David M, Sinama F, Morau D, Marc O. Renewable energy: progressing towards a net zero energy island, the case of Reunion Island. Renew Sustain Energy Rev 2012;16(1):426–42.
[46] Premalatha M, Tauseef SM, Abbasi T, Abbasi SA. The promise and the performance of the world's first two zero carbon eco-cities. Renew Sustain Energy Rev 2013;25:660–9.
[47] Pan W, Ning Y. Delivering zero carbon buildings: the Status Quo and Way Forward. Zero Carbon Build J 2014;1:7–14.
[48] DOE. Building technologies program, planned program activities for 2008–2012. US: Department of Energy (DOE); 2008.
[49] CIC. ZCB fact sheet. Hong Kong: Construction Industry Council (CIC); 2012.
[50] Building and Construction Authority. Singapore's first zero energy building officially opened. The Magazine of the Institution of Engineers; 2009. p. 12–16.
[51] Melink. We are LEED platinum & net-zero energy. ⟨http://www.melinkcorp.com/Melink-Labs/We-Are-LEED-Platinum-and-Net-Zero-Energy.aspx⟩2014 [accessed 10.01.14].
[52] Zuo J, Read B, Pullen S, Shi Q. Carbon-neutral commercial building development. J Manag Eng 2013;29(1):95–102.
[53] Marszal AJ, Heiselberg P. Life cycle cost analysis of a multi-storey residential net zero energy building in Denmark. Energy 2011;36(9):5600–9.
[54] Bryman A. Social research methods. 3rd editon. Oxford, UK: Oxford University Press; 2008.
[55] ZCH. Carbon Compliance: setting an appropriate limit for zero carbon new homes – findings and recommendations. London: Zero Carbon Hub (ZCH); 2011.
[56] NHBC Foundation. Zero carbon: what does it mean to homeowners and housebuilders? Amersham: NHBC Foundation; 2008.